Design and Simulation-Based Parametric Studies of a Compact Ultra-Wide Band Antenna for Wireless Capsule Endoscopy System at Inside Body Environment

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Abstract—**This paper focuses to design a compact (110mm^3) Ultra-Wide Band (UWB) (3.1GHz to 10.6GHz) antenna, which covers almost the whole −10dB impedance matching bandwidth of the UWB range. Two of the main specialties of this article over other related articles are its antenna's wider bandwidth (approx. 7.3GHz) and antenna's simulation environment. No other papers consider such a realistic model to simulate their antenna, before. Due to its wider bandwidth, this antenna can be employed in the Wireless Capsule Endoscopy (WCE) system, which mainly requires a high-speed real-time data transfer-capable antenna. The antenna was examined inside simplified human Gastrointestinal (GI) tract phantoms (Colon, Esophagus, Small Intestine and Stomach) as well as the human Voxel GI tract model by maintaining proper tissue properties for the sake of accurate parametric results. Biocompatible material polyimide was used to construct the capsule wall to fulfill the system's biocompatibility. In the result analysis part, the proposed antenna's SAR (Specific Absorption Rate) or electromagnetic energy amount, consumed by near-side body tissue was considered and found in the acceptable region, according to Federal Communication Commission (FCC)'s regulation. Also, other crucial antenna parameters such as VSWR, reflection coefficient, radiation characteristics, efficiencies, directivity and surface current density were adoptable compare to other related articles. The Finite Integration Technique (FIT) of CST Microwave Studio Suite 2020 was used to investigate the antenna parameters.**

Index Terms—**Wireless capsule endoscopy, Ultra-Wideband (UWB), GI tract, Voltage Standing Wave Ratio (VSWR), specific absorption rate, endoscopic antenna.**

I. Introduction

Nowadays, wireless capsule endoscopy is gaining attention due to its non-invasive process [1]. On the contrary, traditional endoscopy is a painful and time-consuming technique, where a long flexible wire with the attached camera passes through the human throat for examining the Gastrointestinal (GI) tract. Besides, the traditional endoscopy system is unable to reach inside the small intestine part, and that is one of the major drawbacks of the traditional endoscopy system [2]. Whereas, in the wireless capsule endoscopy system, a usual size capsule (27mm × 11mm) with embedded equipment i.e., battery, camera, lighting unit, sensors, antenna and circuits, serves to monitor the condition of the human GI tract. It moves through the entire GI tract and transmits captured images or videos, using its inserted antenna, to its outer receiver so that, the doctor can observe these images or videos in real-time or off-line [3]. For real-time data transfer, the system needs a wideband antenna. In this case, miniaturization of the antenna is a key challenging issue in Wireless Capsule Endoscopy (WCE) system to save the space inside the capsule for other tools [4]. Furthermore, the antenna radiation pattern is needed to be considered in this system, as only an omnidirectional radiation pattern ensures reliable data transmission regardless of location and orientation of the capsule or the receiver [5].

Regarding frequency bands for in-body communication, Federal Communication Commission (FCC) has allowed limited bands for body-related communication, such as Medical Implant Communication Service (MICS), Industrial Scientific and Medical (ISM) [6], Wireless Medical Telemetry Service (WMTS) and Ultra-Wide Band (UWB), among those bands UWB, has the wider frequency range (3.1GHz to 10.6GHz) [7], which allows antennas to operate with a wider bandwidth. FCC regulation for Ultra-wideband (UWB) transmitter is that in real-time at any point, the radiator has a fractional bandwidth equivalent to or more than 0.2 or has a bandwidth equivalent to or greater than 500MHz regardless of the fractional bandwidth [8].

II. Literature Review

At present, several companies, like Intromedic, Olympus [9], Sayaka, Smart Pill, Ipill [1], are serving the WCE sector, but the low data rate is one of the major

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disadvantages of their systems [9]. To solve this drawback, many types of research have been driven on data rate development or bandwidth enhancement of capsule endoscopic antenna, which is closely related to antenna study. Besides that, wider bandwidth is needed to overcome the detuning effect because of different tissue properties throughout the GI tract [3]. Nowadays, different types of antennas are proposed for the WCE system, some of them are for the outer wall of the capsule and others for the inner wall of the capsule. However, outer wall antennas are commercially unacceptable [10], [11], as this type of antennas makes the capsule's structure more complex.

References [1] and [12] introduced two inter wall patch antennas with dimensions of 321.6mm^3 and 921mm^3, respectively. Both of the antennas operate at MICS (medical implant communication service) band, whereat, [1] presented its antenna's data only for inside hollow small intestine and [12] for inside hollow stomach phantom model, therefore, these antennas are not suitable for entire GI tract, as different parts of GI tract have different properties and antenna performance may change inside them. In [4], [7], [13] and [14] the authors designed wideband antennas at UWB frequency, presenting data inside muscle box, it is claimed that these antennas are favorable for WCE system. Also, these antennas did not experience bend condition, but it is evident that bending an antenna affects its performance [15]. Furthermore, to be an antenna for the WCE system, the antenna must show its robust performance at a bending state. Like as [4], [7], [13], and [14], the reference [16] also did not provide its antenna's results at bend condition, however, this antenna was investigated inside different GI tract parts and its resonance frequencies were at UWB frequency range. Reference [17] proposed a meandered line antenna, the results were evaluated inside a homogeneous cylindrical human body model, but the antenna's SAR (Specific Absorption Rate) was not calculated in this article, which makes the antenna unsafe for capsule endoscopy system. A narrow bandwidth (81MHz) conformal inner wall antenna at ISM band (902MHz to 928MHz) was studied in [18], although the parameters were satisfactory, the bandwidth of this design is not wide enough to fit the antenna in WCE system. Furthermore, Miah *et al*. [3] discussed a groundless conformal outer wall loop antenna at the resonance frequency of 433MHz. The bandwidth at −10dB S_{11} of the antenna is 795MHz with achieved gain of −35dBi. As this is an outer wall antenna so the fabrication of the capsule and feeding technique of the antenna would be difficult for commercial manufacturing purposes. Same as [3] the reference [19] also described an outer wall loop antenna, which one was developed at ultra-wide bandwidth (3.1GHz to 4.8GHz), but the absence of SAR leaves a question mark on the antenna regarding patient safety. The cylindrical helical and spiral antennas were suggested in [20] and [21] and the meandered line conformal types were reported in [22] and [23] which operate in different frequency bands such as ISM, MICS, and WMTS. However, all of the antennas have shown a low data rate for transmitting real-time images because of narrow bandwidth.

Most of the prior articles about endoscopic capsule antenna did not consider the proper bio-environment for investigating their respective antennas and some of them did not even calculate the SAR parameter, which is the most important antenna parameter for any in-body antenna. So, this paper aims to design a miniaturized antenna that fulfills all the demands i.e., exact bio-environment for the antenna testing, SAR calculation and wider bandwidth achievement, those are mandatory for an antenna to be a capsule endoscopic antenna. This article is organized as follows: Section III deals with the (A) designing specifications of the antenna, (B) capsule, digestive phantoms modeling and (C) antenna testing environment related discussion. Then, in Section IV, the results of the conferred antenna are presented inside GI phantom models. After that in Section V, the Results are again studied inside the voxel body model to check the credibility of the antenna parameters. Proposed antenna's results' summary for different digestive part phantom models and the comparison of the work with other reported analogous works are studied in Section VI. Finally, this article is concluded in Section VII.

III. Model and Design

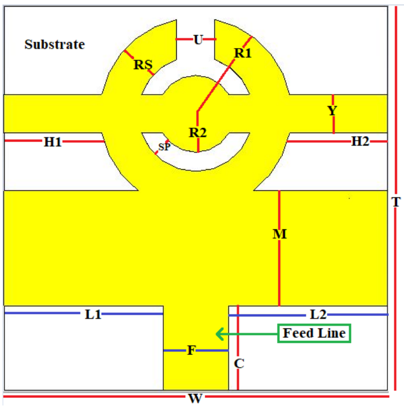
A. Antenna Designing Specifications

The main purpose of this article is to design a compact antenna that suits at the inner wall of the capsule. To design the antenna (Fig. 1), the worksheet of CST MICROWAVE STUDIO SUITE 2020 is utilized. At first, a 10mm × 10mm × 0.60mm substrate plate is created, using Rogger R03010 from the CST material library, which contains relative permittivity (ε_r)=11.2 and loss tangent (tanδ)= 0.0022. The high-permittivity dielectric material is assigned in antenna designing to shortening the effective wavelength of the antenna that ultimately makes the design miniaturized. Then, a ring shape radiator (outer radius, R_1=2.64mm) with a solid circle (radius, R_2=1) at center point is designed on the substrate, and copper is used as radiator material, having a thickness of 0.25 mm. The radius of the ring shape radiator is calculated by using equation 1[4].

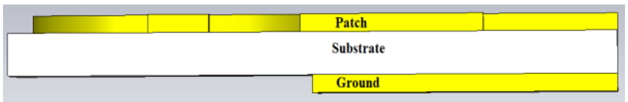
$$A = \frac{1.841\nu}{2\pi f_r \sqrt{\varepsilon_r}}$$

where A= R_1 is the radius of the ring shape radiator, ν is the speed of light in the medium, f_r is the tuning frequency and ε_r is the relative permittivity of the antenna's substrate.

From Fig. 1 (a) it can be seen that the ring and centered point solid circular shape radiator are added to each other with slots. Also, a rectangular shape slot (U) is cut from the upper side of the ring-shape radiator to shift the antenna resonance frequency at the lower band. Moreover, a rectangular shape radiator is designed just at the below of the ring shape radiator. Furthermore, a feed line is introduced afterward of that rectangular shape radiator for excitation of the antenna by using a waveguide port. All these slots are proposed to get desired frequency bandwidth, introducing these slots mainly lengthen the radiator path, which develops the current flow path as well as increases the inductances of the antenna that decreases the quality factor of the antenna, as a result, antenna bandwidth improves itself [24], [25]. A partial saw-tooth ground plate is established at the other side of the substrate (Fig. 1 (b)) for further wider bandwidth and to minimize the antenna area [26]. The study shows that the capacitive loading effect happens due to a partial saw-tooth ground plate as it switches the space between the ground and the lower side of the planer antenna, as a consequence, the antenna provides wider bandwidth. Antenna layers dimensions are presented in Table I.



(a)



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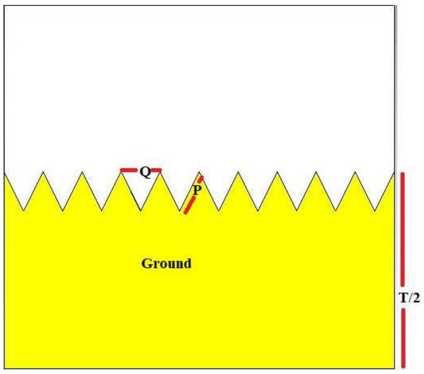
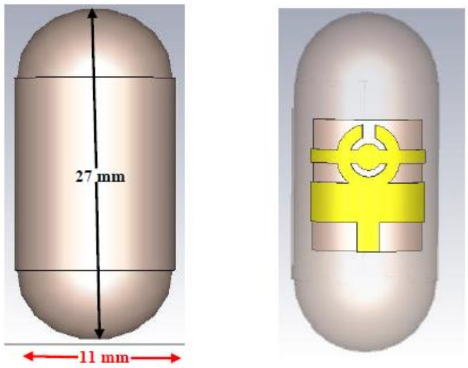


(c)

Fig. 1. Proposed antenna: (a) Front view, (b) side view, and (c) back view.

TABLE I: GEOMETRICAL DIMENSIONS OF THE ANTENNA PLATES

Antenna plate (material)	Symbol and value (mm)
Radiator (copper)	U = 1; RS = 1.04; R_1 = 2.64; R_2 = 1; SP = 0.6; Y = 1; H_2 = H_1 = 2.36; M = 3; L_1 = L_2 = 4.15; F = 1.70; C = 2.20; Thickness = 0.25
Substrate (Rogger R03010)	W = 10; T = 10; Thickness = 0.60
Ground (copper)	$T/2$ = 5; P = 1.12; Q = 1; Thickness = 0.25



(a) (b)

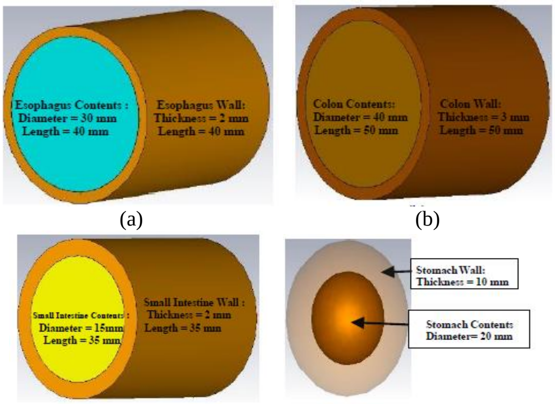
Fig. 2. Capsule: (a) Solid view with dimensions and (b) transparent view with the inserted bent antenna at the inner wall.

B. Capsule and GI Phantoms Designing Specifications

When it comes to design a device, which is about to operate inside body condition, the device's biocompatibility must be considered and that can be ensured only by assigning proper insulating material such as alloplastic [27], titanium or titanium alloy [28], Teflon [29], polyimide [30] to wrap the antenna along with other accessories i.e., power source, sensors, circuit board, etc. of the system because direct contact between antenna and body tissue or without proper insulation of the system would damage the surrounding tissues as well as the system itself by inducing sort circuit as the body tissues have electrically conductive properties [15]. In the capsule-endoscopy system, the capsule wall mainly works as a shield or insulation for the system. In our case, we have used bio-material polyimide (relative permittivity, ε_r=3.5, loss tangent, tanδ =0.0027, and thickness =0.1mm) as a capsule wall. Furthermore, the length and diameter of the capsule are 27mm and 11mm (Fig. 2), respectively, which complies with the commercial endoscopic capsule size. So, the total volume of the capsule is $(3.1416\times5.5^2\times27)$mm^3=2565.9mm^3, where the 110mm^3 volumed-antenna occupies only 4.29 % of the capsule's area and leaves 95.71 % for other tools of the system.

An endoscopic capsule travels through the entire digestive tract, namely, esophagus, colon, or large intestine, small intestine, and stomach [16]. Numerous reliable sources [31]-[33] reported that these organs (GI tract: colon, esophagus, small intestine, stomach, etc.,) are split into two parts such as respective organ's wall and lumen, where the lumen is mainly tube, which contains human consumed air, food, liquid, and wastage, in a word contents, but during the capsule endoscopy procedure GI tract contains mostly in-body air and liquid [34]. However, many former papers [1], [12], and [16] designed their GI tract models, considering only the organ's wall, which might lead their results of the antenna parameter to inaccuracy.

Therefore, we have designed GI models as shown in Fig. 3 by maintaining proper dimensions (Table II) and body parts of those organs, taken into account [35]-[37] as a reference, to simulate the antenna in a proper bio-environment. Also, it is exhibited in Fig. 3 that all of the models contain two parts: the respective organ's wall and contents. Dimensions of these GI tract's organs may vary depending on age and sex. After designing the GI models we have also modeled the outer body layers such as muscle, fat, and skin, taking [28] as reference for dimensional values (Table II), to those GI models in a sequential manner as it can be seen from Fig. 4. Moreover, during the designing of this phantom the dielectric and other important properties are taken care which is tabulated in Table III.



(a) (b)

(c) (d)

Fig. 3. Designed models with dimensions labeling: (a) Esophagus, (b) Colon, (c) Small intestine, and (d) Stomach.

TABLE II: BODY LAYERS' DIMENSIONAL FEATURE

Body layer	Dimension (mm)
Esophagus	**Contents:** diameter = 30; length = 40
	Wall: thickness = 2; length = 40
Colon or large intestine	**Contents:** diameter = 40; length = 50
	Wall: thickness = 3; length = 50
Small intestine	**Contents:** diameter = 15; length = 35
	Wall: thickness = 2; length = 35
Stomach	**Contents:** diameter = 20
	Wall: thickness = 10
Muscle	Thickness = 35
Fat	Thickness = 7
Skin	Thickness = 4

C. *Antenna Testing Environment*

After completing the designing of the capsule and the phantom models, the capsule with the antenna inside at the inner wall is placed inside at the center point of those phantoms as x-axis oriented, which means the lengthy dimension of the capsule is alined with the x-axis, to investigate the antenna parameters. Fig. 4 exhibits the general cross-sectional sight of all the phantom models, indicating antenna position.

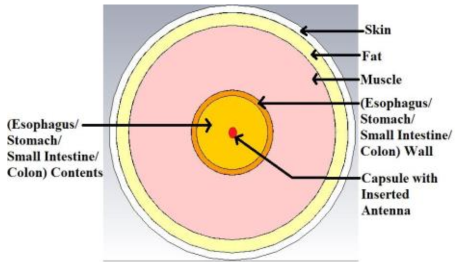
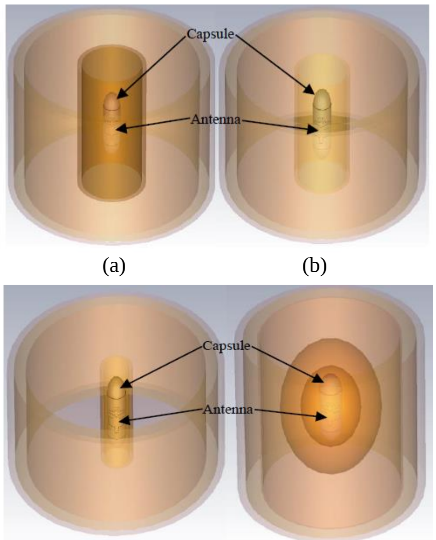


Fig. 4. The cross-sectional common view of the GI tract phantoms, where the capsule and the body layers are indicated.



(a) (b)

(c) (d)

Fig. 5. Implantation positions of the capsule with the inserted antenna inside phantom models: (a) Esophagus, (b) colon or large intestine, (c) small intestine, and (d) stomach.

To model the phantom, tissue properties are needed to set properly for errorless simulation results. Dielectric properties (relative permittivity, conductivity, and loss tangent) of any tissue are frequency-dependent [3]. Therefore, in this study dielectric properties' values of the tissues are fixed at 5GHz as we are about to design a UWB antenna [16]. Furthermore, tissues' biological and physical properties can change depending on age and wet or dry skin. Therefore, authentic sources [38]-[41] are explored to come up with the values of the biological and physical properties of the tissues. Implantation positions of the capsule with the antenna inside different GI tract models can be observed from Fig. 5.

TABLE III: DIELECTRIC (AT 5 GHZ), BIOLOGICAL AND IMPORTANT PHYSICAL PROPERTIES OF THE TISSUE

Tissue	Relative permittivity	Conductivity (s/m)	Loss tangent	Thermal conductivity (w/k/m)	Specific heat (j/k/kg)	Metabolic rate (w/m^3)	Blood flow Coefficient (w/k/m^3)	Density (Kg/m^3)
Esophagus contents	57.89	5.16	0.32	0.5	3500	0	0	1040
Esophagus wall	57.89	5.16	0.32	0.5	3500	2000	9000	1040
Colon contents	46.4	4.7	0.36	0.6	3600	0	0	1060
Colon wall	46.4	4.7	0.36	0.6	3600	9000	50000	1060
Small intestine contents	49.98	5.75	0.41	0.6	3600	0	0	1030
Small intestine wall	49.98	5.75	0.41	0.6	4200	9000	50000	1030
Stomach contents	57.89	5.16	0.32	0.5	3600	0	0	1050
Stomach wall	57.89	5.16	0.32	0.5	3600	5000	30000	1050
Muscle	49.54	4.04	0.29	0.5	3500	500	3000	1060
Skin	5.03	0.24	0.17	0.2	2500	300	2000	900
Fat	35.77	3.06	0.31	0.3	3500	2000	9000	1100

* Only important properties have been mentioned in the table.

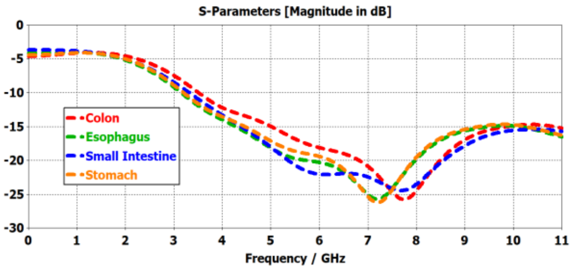


Fig. 6. Reflection coefficient versus frequency (0GHz to 11GHz) response curves of the antenna inside different GI tract models.

IV. Result Analysis of the Antenna Inside GI Tract Phantom Models

After placing the antenna inside the GI models as it is shown in Fig. 5, the antenna parameters are investigated. The results of the antenna parameters are presented below.

A. S-Parameter or Reflection Coefficient

Antenna's S-parameter (S_{11}) is widely known as reflection coefficient, which provides information about how much power is reflected by the antenna [6]. According to antenna study, this value must be less than −10dB, greater than that means a major portion (90%) of the input energy is radiated, which is not acceptable [28]. Fig. 6 shows the antenna's reflection coefficient responses against frequency for all of the GI tract models, where the *X*-axis represents the frequency in GHz and *Y*-axis represents the magnitude of the reflection coefficient in dB. The antenna's responses are examined from 0GHz to 11GHz, as the aim of this study is to design a UWB antenna. On the other hand, data transmission rate at higher frequencies, such as greater than 10.6GHz, is very low [42]. The resonance frequencies of the antenna are found at 7.744GHz, 7.205GHz, 7.689GHz, and 7.205GHz inside the colon, esophagus, small intestine, and stomach model, respectively. Furthermore, the minimum s-parameter value of the antenna is −26.20dB at the resonance frequency of 7.205GHz, inside the stomach phantom and the maximum is noted −24.45dB inside small intestine phantom at 7.689GHz. The achieved fractional bandwidths of the antenna, measured at −10dB S_{11} horizontal level, at UWB frequency range (3.1GHz to 10.6GHz), are above 91% (detail bandwidth ranges are mentioned in Table IV) for all of the GI phantoms, which is considerably higher compared to other reported endoscopic antennas.

B. Voltage Standing Wave Ratio (VSWR)

The voltage standing wave ratio is shortly known as VSWR, ensures the antenna's impedance matching-ability with the transmission line of the system [43]. VSWR is closely related to the reflection coefficient. According to antenna study, the minimum VSWR value of any antenna can be 1 and the acceptable maximum value should be 2, to be an effective antenna for any in-body communication system [6]. Fig. 7 is depicting the antenna's VSWR values (Y-axis) concerning frequency (X-axis) for inside all four designed GI phantoms, indicating with different colors, where it can be seen that, although the VSWR values are greater than 2 at lower frequency ranges, such as 0GHz to 3.51GHz (Colon), 0GHz to 3.15GHz (Esophagus), 0GHz to 3.32GHz (Small Intestine) and 0GHz to 3.2GHz (Stomach), at higher than those ranges it decreases to below 2, means the antenna is well-matched with the system throughout the interested band. Also, the antenna's lowest VSWR value is 1.085 at the center frequency of 7.744GHz, inside the colon model and the highest VSWR value is found to be 1.13 at the center frequency of 7.689GHz, inside the small intestine.

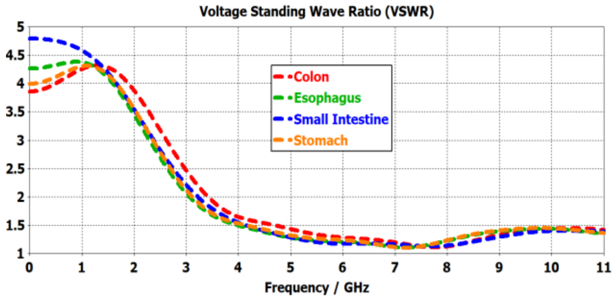


Fig. 7. VSWR versus frequency response curves of the antenna inside different GI tract models.

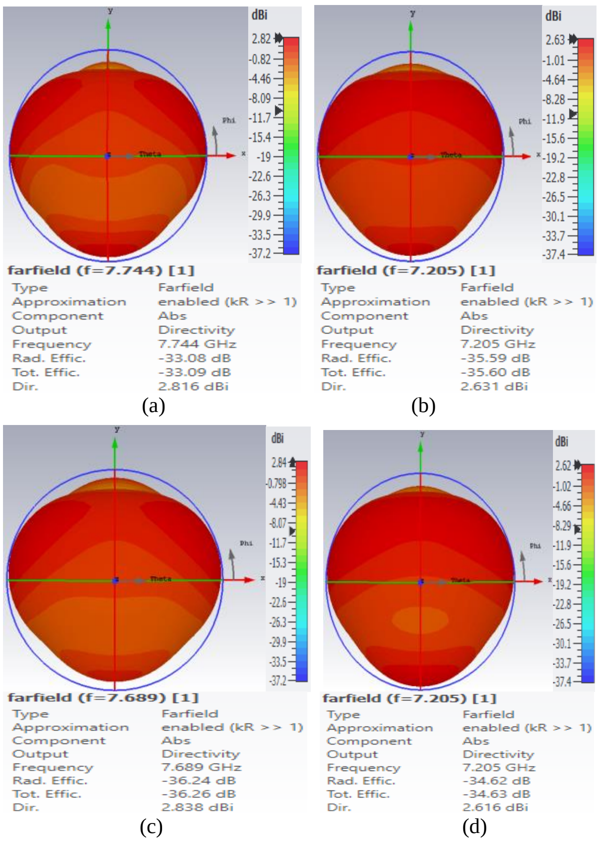


Fig. 8. 3D far-field views of the antenna radiation patterns inside GI models: (a) Colon (at 7.744GHz), (b) Esophagus (at 7.205GHz), (c) Small Intestine (at 7.689 GHz) and (d) Stomach (at 7.205GHz).

C. Radiation Pattern

The antenna's 3D-far field radiation patterns of directivities are studied inside the GI phantoms at their respective tuning frequencies by using the CST simulation tool. The antenna directivities are observed to check whether the antenna radiations concentrate in all directions or not, as the antenna needs to transmit data to all directions regardless of locations and orientations. Theoretically, an antenna has directivity of 0dBi, when it provides equal radiation to all directions [15]. From Fig. 8, it is evident that the designed antenna has equal radiation to almost all directions. The measured directivities' values of the antenna vary from 2.62dBi (inside the stomach model at 7.205 GHz) to 2.84dBi (inside the small intestine at 7.689 GHz). Moreover, the recorded minimal total efficiency and radiation efficiency values of the antenna are –36.24dBi and –36.26dBi, respectively, inside the small intestine model at the frequency of 7.689GHz and maximal total efficiency and radiation efficiency, are found –33.08dB and –33.09dB, respectively, inside colon model at 7.744GHz. Low efficiencies are very common for bio-medical in-body antennas as this type of antennas experiences the super lossy tissues around them.

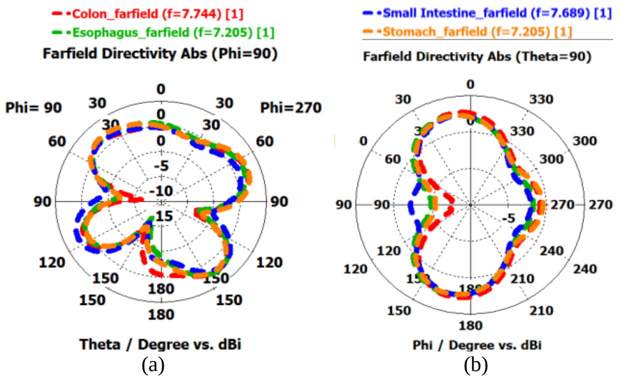


Fig. 9. Antenna's polar views for the far-field directivities inside Colon, Esophagus, Small Intestine, and Stomach model, simulated at their respective resonance frequencies: (a) at phi = 90 degrees (Elevation) (b) at theta = 90 degrees (Azimuth).

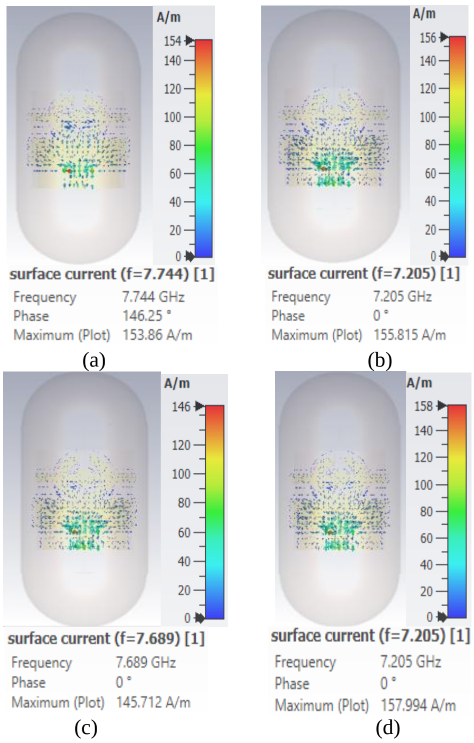


Fig. 10. Surface currents of the antenna inside phantom models: (a) Colon (at 7.744GHz), (b) Esophagus (at 7.205GHz), (c) Small Intestine (at 7.689GHz), and (d) Stomach (at 7.205GHz).

Polar views (2D) of the antenna's far-field directivities are presented in Fig. 9 for two different angles of views (Elevation and Azimuth) for a better understanding of the antenna radiation patterns in terms of degree. It is certain from Fig. 9 that the antenna has almost Omni-directional radiation patterns for both angles of views.

D. Surface Current

The proposed antenna's surface currents are calculated (Fig. 10), at different immersed situations inside GI models, at their center frequencies. The highest and lowest figures of the surface currents are noted 158A/m (inside the stomach model at 7.205GHz) and 146A/m (inside small intestine at 7.689GHz), respectively. Note that the maximum current flow through the feed line in all of the cases.

E. Specific Absorption Rate (SAR)

Specific Absorption Rate, shortly SAR is one of the most crucial antenna parameters to be considered for any bio-medical antenna, which is about to operate in-body or on-body communication system, as it is related to patients safety. SAR indicates the amount of electromagnetic energy, absorbed by the near-side body tissue of the antenna. To comply with the FCC's regulation regarding SAR-standards, the SAR value of an antenna should not exceed 1.6w/kg for 1 gram body tissue [12]. For this antenna, SAR values vary from 1.05 w/kg to 1.1w/kg (Fig. 11), those are measured inside different GI models i.e., colon, esophagus, small intestine, and stomach, for 1mw input power.

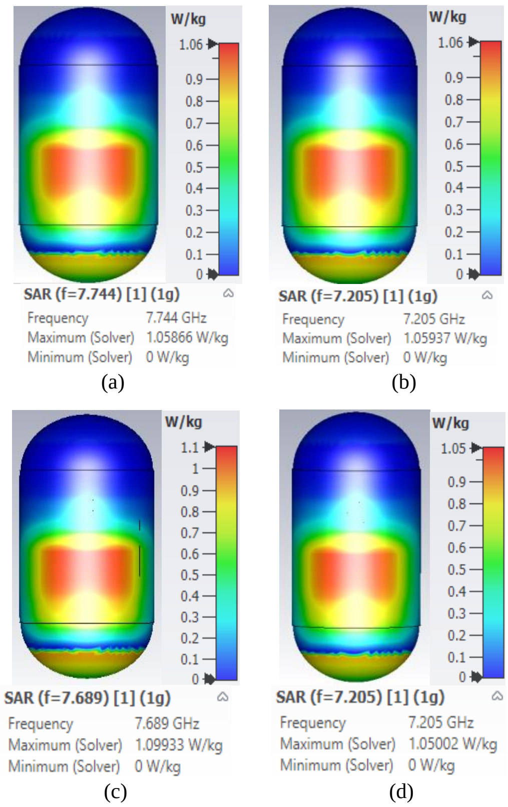
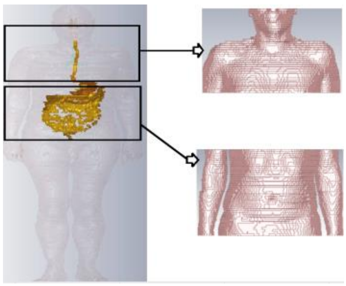
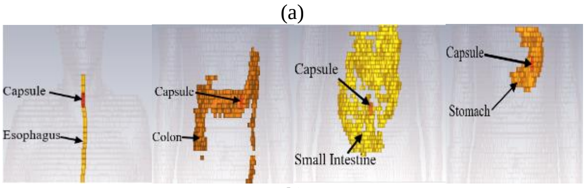


Fig. 11. Measured SAR values of the antenna inside phantom models: (a) Colon (at 7.744 GHZ), (b) Esophagus (at 7.205GHz), (c) small intestine (at 7.689GHz) and (d) stomach (at 7.205GHz).



(a)



(b)

Fig. 12. (a) 3-D human voxel body model with selected torsos and (b) implanted positions of the capsule, with the antenna at the inner wall in them.

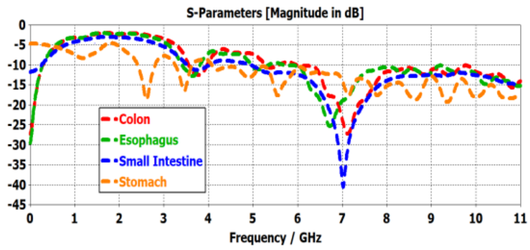


Fig. 13. S_{11} versus frequency response curves inside voxel GI tract models for various positions.

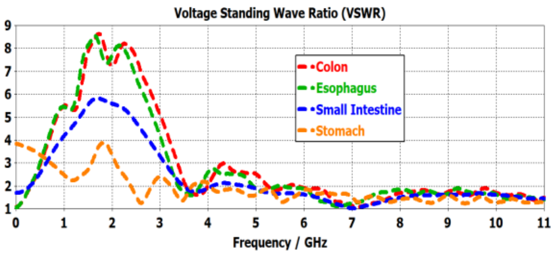


Fig. 14. VSWR versus frequency curves of the antenna for different positions, inside voxel GI tract models.

V. Result Analysis of the Antenna Inside Realistic Body Model

The antenna is also implanted inside a realistic human voxel body model named Gustav, which is chosen from CST MICROWAVE STUDIO SUITE 2020 voxel family to check the robustness of the antenna performances. Due to the limitation of computing resources, two torsos with similar volumes (290 mm × 300mm × 310mm) are considered to overcome the limitation during the simulation. The full-body model with selected torsos and implanted positions of the capsule with antenna, inside those torsos are illustrated in Fig. 12. The capsule is implanted approximately 55 mm, 30 mm, 60 mm, and 75 mm away from the nearest body surface inside the colon, esophagus, small intestine, and stomach, respectively. The responses of the simulated S_{11} (reflection coefficient) in contrast to frequency (GHz) are presented in Fig. 13. Comparing the S_{11} curves of Fig. 6 with Fig. 13, it can be commended that the −10dBi impedance matching bandwidths at the UWB frequency range are relatively better inside phantom models (Fig. 6). Apart from UWB (3.1GHz to 10.6GHz) frequency boundary, the antenna also supports 0 GHz to 0.278GHz when it passes through the colon, esophagus, and small intestine of the voxel body model. Also, inside the stomach of the voxel model, the antenna covers 2.41GHz to 2.86GHz frequency range that lies under the ISM band.

The antenna supports almost the whole area of the UWB range (3.1GHz to 10.6GHz) for voxel model implantation too, which can be realized from Fig. 13 and Fig. 14. Also, The VSWR (considering only less than 2 values) curves in Fig. 14 indicate that the antenna is well-matched with the system throughout the UWB frequency range in the voxel GI tract model as well. Furthermore, Antenna's other parameters such as efficiencies and SAR are also quite satisfactory inside the voxel GI model.

VI. Comparison Analysis

Simulated results of the antenna for various orientations in GI phantom models have been summarized in Table IV. Note that the bandwidth ranges are calculated at the reflection coefficient (S_{11}) equal to −10dB level. From Table IV, antenna's VSWR values can be observed, which depict the antenna's impedance matching capability with the transmission system as less than 2 value is found for all of the GI phantom models implantations. Also, efficiencies of the antenna are far better to compare to the antenna efficiencies in [1], [13], [16], [44] and [45] and finally, the antenna SAR values, less than 1.6 w/kg over 1 gram body tissue, fulfill the antenna safety demand for patients, according to FCC standards.

TABLE IV: Parametric Results of the Antenna for Different GI Tract Phantom Models

Parameter	Colon	Esophagus	Small intestine	Stomach
Resonance frequency (GHz)	7.444	7.205	7.689	7.205
Bandwidth the range at UWB (GHz)	3.51 to 10.6	3.15 to 10.6	3.32 to 10.6	3.202 to 10.6
Reflection coefficient (dB)	-25.77	-25.70	-24.45	-26.206
VSWR	1.109	1.109	1.127	1.102
Total efficiency (dBi)	-33.09	-35.60	-36.26	-34.63
Radiation efficiency (dBi)	-33.08	-35.59	-36.24	-34.62
Directivity (dB)	2.816	2.631	2.836	2.616
SAR (w/Kg) (1 gram)	1.06	1.06	1.1	1.05

A brief comparison, in terms of antenna volume, bandwidth, simulation environment and antenna location at the capsule, of the antenna with other related published papers is presented in Table V. Although this design is not the most compact antenna comparing with [3], [7], [16] and [18] it does not matter at all, as this antenna is perfectly fit-able inside the capsule and occupies only 4.23% of the total area of a commercial size endoscopic capsule. On the other hand, bandwidth is one of the major demerits of all those reported articles, the widest bandwidth is 2.9 GHz [16] among those papers, which is not sufficient for a WCE system, but the conferred antenna overcome this issue with much widest bandwidth (approx. 7.3 GHz) comparing to all of them. Also, the antenna was simulated inside gastrointestinal organs as well as realistic Voxel GI models by maintaining proper tissue properties, which helps to achieve the realistic parameter results. In a word, this antenna may be the first antenna that delivers such widest bandwidth in such a realistic simulation domain.

TABLE V: ANTENNA'S PERFORMANCE COMPARISON WITH OTHER REPORTED WORKS

Reference	Size (mm^3)	Bandwidth	Simulation Environment	Antenna location at the capsule
[1]	321	0.103GHz (0.348GHz to 0.451GHz)	Hollow small intestine phantom	Inner-wall
[3]	83.44	Around 0.795GHz (0.309GHz to 1.104GHz)	Muscle and GI tract phantoms	Outer-wall
[7]	82	3.91GHz (3.45GHz to 7.5GHz)	Muscle phantom	No capsule is considered
[16]	90	2.9GHz (3.1GHz to 6GHz)	Simplified GI tract phantoms without considering contents (lumen)	No capsule is considered
[18]	30	0.081GHz (0.861GHz to 0.942GHz)	Muscle Phantom	Inner-wall
[19]	134	1.7GHz (3.1GHz to 4.8GHz)	Muscle phantom	Inner-wall
[44]	180.12	0.541GHz (0.284GHz to 0.825GHz)	Simplified body phantom (muscle, bone, blood, fat)	Inner-wall
[46]	135	1GHz (3.5GHz to 4.5GHz)	Small intestine phantom considering the only wall	Inner-wall
This work	110	Around 7.3GHz (app. 3.3GHz to 10.6GHz)	Simplified GI tract phantoms with considering contents (lumen)	Inner-wall

VII. CONCLUSION AND FUTURE AIM

This study has described a circular shape low profile patch antenna in which one is capable to transmit data with high speed, as a result of its approximate 7.3GHz bandwidth at UWB range, which is the key specialty of the design. In addition, the antenna's Reflection co-efficient values (s-parameter) were also found at a good range (–24.45dB to –26.206dB) inside different GI models. Furthermore, the directivity values between 2.62dBi to 2.81dBi, means this is an Omni-directional antenna. The results analysis of the antenna with other works has been done to find out its superiority over them and it secured its position, regarding bandwidth and simulation setting. Specific Absorption Rate (SAR) assessment also confirmed the antenna's bio-compatibility inside the human body. Finally, as this antenna's performances have been evaluated maintaining all terms and conditions for a wireless endoscopy system so, it is evident that it will perform as same in the practical field too, however, in recent future we will work towards the fabrication of the antenna and measure its performances inside a real body.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Md. Abdullah Al Rakib and Shamim Ahmad came up with the research idea by studying related articles and conducted the designing and simulation part. Tareq Mohammad Faraqui and Mainul Haque wrote the manuscript. Sharifa Akter Rukia and Sumaiya Nazmi analyzed the data and helped with the referencing part. Sharifa Akter Rukia and Sumaiya Nazmi also prepared the manuscript according to the reviewers' comments. All authors had revised the final version and approved it for publication.

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